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COMPARATIVE COMBUSTION PROPERTIES OF RAW AND WASHED DONKIN COALS IN THE CCRL PILOT-SCALE BOILER

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APRIL 1987

(CANMET)

ENERGY RESEARCH LABORATORIES
DIVISION REPORT ERL 87-50(IR)

59 pp

MICROMEDIA

88-01548/

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by

G.N. Banks*, J.K.L. Wong** and H. Whaley***

ABSTRACT

The combustion performance of raw Donkin coal (run of mine) and three levels of cleaned (washed) Donkin coal was compared with that of a commercially available thermal bituminous coal from Western Canada. Tests were conducted in a pilot-scale pulverized coal-fired research boiler located at the Energy Research Laboratories (ERL) in Ottawa.

The three cleaned coal samples were obtained from the CANMET Coal Research Laboratories coal cleaning facility in Devon, Alberta. Chemical, physical, petrographic and thermogravimetric analyses were performed on samples of the coals as they were received in Ottawa. Each coal flowed readily through the ERL pilot-scale conveying and coal-handling system.

The coals, which ground readily to produce a consistent size product from the pulverizer, ignited easily to produce stable flames at greater than 96% combustion efficiency. The highest combustion efficiencies were obtained with the more finely ground coal feeds. The washed Donkin coal, containing the lowest ash content, gave the highest combustion efficiency.

The ash from each of the Donkin coal samples was quite fluid and slagged readily in the refractory-lined furnace bottom, whereas the ash deposits on the water-walls and superheater surfaces were light and powdery and did not constitute a fouling problem.

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Without exception, the washed Donkin coal samples burned at a higher combustion efficiency, a lower SO_2 level in the flue gas, and a decreased volume of ash and slag on the heat transfer surfaces and the furnace bottom than was obtained with the Donkin raw coal. Washing the Donkin coal did not appear to cause any significant operational difficulties in burning the coal, and as outlined in an earlier report (1) the combustible content of the fly ash can be significantly reduced by increasing the combustion residence time.

COMPARAISON ENTRE LES PROPRIÉTÉS DE COMBUSTION DES CHARBONS DONKIN BRUTS ET LAVÉS DANS UNE CHAUDIÈRE PILOTE DU LRCC

par

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RÉSUMÉ

Le rendement de combustion d'un charbon Donkin brut (tout venant) et trois rangs de charbons Donkin lavés a été comparé avec le rendement d'un charbon thermique bitumineux de l'Ouest canadien. Des essais ont été effectués dans une chaudière expérimentale à échelle pilote chauffée avec du charbon pulvérisé, située aux Laboratoires de recherche sur l'énergie (LRE) à Ottawa.

Les trois échantillons de charbons lavés ont été obtenus de la laverie de charbon des laboratoires de recherche sur le charbon du CANMET à Devon en Alberta. Des analyses chimiques, physiques, pétrographiques et thermogravimétriques ont été effectuées sur les échantillons de charbon tel que reçu à Ottawa. Chaque charbon circulait bien à travers les systèmes de convoyeurs et de transport à échelle-pilote du LRE.

Les charbons se pulvérisaient sans difficulté pour produire un produit de taille régulière qui s'allumait facilement et produisait des flammes stables avec un rendement de combustion plus élevée que 96 %. On a obtenu des rendements de combustion plus élevés avec des charbons pulvérisés plus finement. Le charbon Donkin lavé, contenant la plus faible teneur en cendres, a donné le rendement de combustion le plus efficace.

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La cendre provenant de chaque échantillon de charbon Donkin était assez fluide, et formait un dépôt sur la surface réfractaire au fond de la chaudière, tandis que les dépôts de cendres sur les surfaces du surchauffeur étaient légers et poudreux, et ne présentaient pas de problème d'encrassement.

Les échantillons de charbon Donkin lavé ont brûlé sans exception à un taux de rendement en combustion plus élevé avec une teneur plus basse en SO_2 dans les gaz de carneau et ils ont produits un volume moins élevé de cendres et de scories sur les surfaces du surchauffeur et au fond de la chaudière par rapport aux charbons bruts Donkin. Le lavage des charbons Donkin n'a pas semblé avoir causé des difficultés opérationnelles importantes lors de la combustion du charbon et, tel que souligné dans un rapport antérieur (1) la teneur combustible des cendres volantes peut être considérablement réduite en augmentant le temps de séjour de combustion.

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INTRODUCTION

As an addendum to an International Energy Agency (IEA) research program, CANMET has agreed to conduct pilot-scale combustion trials on selected raw and cleaned coals. The IEA Coal Cleanability and Combustion Characterization Project was formed to investigate the effect of coal beneficiation on the combustion properties of high ash, slagging thermal coals. Due to the diminishing quality of thermal coals and the increasing world recognition of environmental concerns, interest in the effects of coal beneficiation on the combustion performance of cleaned coals has increased significantly.

The Canadian test coal in the IEA series was from the Cape Breton Development Corporation's (CBDC) Prince mine, located on the Hub Seam in the Sydney coalfield. Cleaned coal test samples were produced from the Prince mine raw coal by the Electric Power Research Institute (EPRI) Homer City coal cleaning facility in the USA and CANMET's Coal Research Laboratories (CRL) coal cleaning facility in Devon, Alberta. These coal samples were shipped to Ottawa, Ontario, where combustion performance evaluation tests were carried out by CANMET's Energy Research Laboratories (ERL) in a pilot-scale pulverized-coal-fired research utility boiler. Combustion results from the cleaned and raw Prince mine coals were compared with each other and with those from a commercially available bituminous thermal coal sample from Western Canada. The results of this testwork were reported previously (2). A second coal was obtained from the New Brunswick Coal Company's Minto Coalfield mine located at Salmon Harbour, New Brunswick. Three cleaned coal test samples were produced from the Minto bituminous raw coal at the CRL facility in Devon, Alberta and shipped to Ottawa for combustion performance evaluation tests. The results of these tests are recorded elsewhere (3).

A third coal in this series was obtained from the CBDC's Harbour seam coal reserves in the Donkin coal block, Cape Breton, Nova Scotia. Three cleaned coal test samples were produced from the Donkin high-volatile bituminous raw coal at the CRL facility in Devon, Alberta and shipped to Ottawa for combustion evaluation tests. The combustion results on the Donkin raw coal and a sample of cleaned coal (washed at the CBDC Victoria Junction Preparation Plant) were reported previously (1). The results obtained with the raw coal sample are reiterated in the present report for more direct comparison purposes.

This report describes the objectives of the Donkin coal project and gives the analyses of the coals. Based on these analyses, the coals' apparent quality, combustion reactivity, and potential ash slagging and fouling properties are assessed. The facilities and equipment utilized and the operational procedures selected to evaluate the coals' actual combustion performance are then described and the actual pilot plant performance is compared with predicted values.

RESEARCH OBJECTIVES

The objectives of this project were:

1. To quantify coal quality, chemistry and petrography.
2. To determine coal comminution and handling characteristics.
3. To evaluate the combustion performance of the pulverized coal at two fineness levels and at an excess air level corresponding to 4% oxygen in the flue gases.
4. To characterize the particulate and gaseous pollutants generated during combustion.
5. To assess the slagging and fouling potential of the coal ash constituents on radiant heat transfer surfaces and superheater tubes.
6. To assess the electrical resistivity characteristics of the fly ash and the ease of fly ash collection by electrostatic precipitation.
7. To generate coal combustion charts based on heat losses calculated from the coal analyses.

COAL CHARACTERISTICS

HANDLING AND PREPARATION

Samples of the three washed Donkin coal products were delivered to the Energy Research Laboratories in sealed 45-gallon drums. It was noted from the chemical analyses given in Table 2 that a 70% reduction in the ash content of the Donkin raw coal resulted in a 43% reduction in the sulphur content. A 70% reduction in the ash content of the Prince mine coal resulted in only a 24% reduction in its sulphur content (2). The Prince mine and Donkin raw

coals each has about 60% of their sulphur in the pyritic form, but the Donkin raw coal contained 70% less ash and 50% less sulphur than the raw Prince mine coal. However, similar to the Prince mine and the Minto coals the Donkin coal products with their "as received" moisture were free flowing and no problems were experienced in feeding them through the pilot-scale coal handling system.

COMBUSTION REACTIVITY

The screen and proximate, ultimate and ash analyses of the coal samples are listed in Tables 1 to 4. These analyses and the petrographic data given in Table 5 and Fig. 1 to 3 provide a guide for predicting "Combustion Reactivity". This term is generally understood as the ability of a coal to ignite readily and to produce a stable flame with acceptable carbon burn-out, without the necessity of support firing, when applied to the assessment of a potential thermal coal.

The volatile matter content of 36-38% suggests that these coals should ignite readily and the indicated percentage of reactive macerals in the coals (Table 5) is quite high (87-91%), which suggests that carbon burn-out of the coal should be good. The higher mean reflectance of the Donkin coals suggests that their reactivities should be lower than that of the reference coal. Figure 1 illustrates the influence of different coal macerals on combustion reactivity and carbon burn-out. It indicates that the combustion efficiency of the Donkin coals (raw and washed) should be equivalent to that obtained for the reference thermal coal, due to the equivalent or greater amount of exinite and reactive vitrinite macerals.

Another method used to predict the combustion reactivity of the coal is to determine its burn profile in air by thermogravimetric analysis (Fig. 3). The reference coal reached its highest devolatilization rate of 7.8%/min. at a reaction temperature of 400°C. While the raw Donkin coal reached its highest devolatilization rate of 6.8%/min. at about the same reaction temperature as the reference coal, it had a later devolatilization peak of 6.1%/min. at about 480°C. The three washed Donkin coal samples also exhibited two devolatilization peaks with the earlier one occurring at 400-450°C at a rate of 5.5 to 6%/min. and a later one (of about the same magnitude) at 500°C. The results of thermogravimetric analysis indicate that the combustion efficiency of the Donkin raw coal will be lower than that of the reference coal and washing the Donkin coal will tend to further reduce the combustion efficiency of the coal.

The overall results of these bench-scale analytical tests indicate that the Donkin coal samples should ignite readily to produce a stable flame, but their combustion efficiency will be lower than that of the thermal reference coal.

Combustion charts, based on the ultimate analyses of the raw Donkin coal sample, are given in Appendix A. These charts provide a rapid, graphical means of determining boiler efficiency by the indirect ASME heat loss method.

HIGH TEMPERATURE ASH DEPOSITS

Two general types of high-temperature ash deposits can occur on the gas-side surfaces of coal-fired boilers:

1. Slagging - fused deposits that form on surfaces exposed predominantly to radiant heat transfer, such as on refractory furnace bottoms.
2. Fouling - high temperature bonded deposits that form on surfaces exposed predominantly to convective heat transfer, such as on superheater or reheater surfaces. Such deposits are not easily removed by soot-blowing procedures.

SLAGGING INDICATORS

The slagging potential of a coal can often be assessed by using indices or composite parameters to describe the nature and severity of the slag deposits (4). Two common indices for determining the slagging potential of the coal ash and furnace deposits are described below:

1. The base/acid ratio (B/A) is defined as:

$$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2} ,$$

where each oxide is expressed as a percentage of the total ash. A maximum of 0.5 for the base/acid ratio has been suggested for dry-bottom pulverized-fired units, although this is not a necessary restriction. Values below 0.27 indicate that slagging is an unlikely problem at normal furnace operating temperatures.

2. Potential slagging temperature (T_{ps}) is defined as:

$$T_{ps} = \frac{HT + 4IT}{5} \,^{\circ}C \quad ,$$

where IT is the minimum temperature at which initial ash deformation occurs (normally in a reducing atmosphere) and HT is the maximum temperature at which hemispherical deformation occurs (normally in an oxidizing atmosphere). Temperature values greater than 1340°C indicate a low slagging potential, whereas values less than 1150°C indicate a severe slagging potential.

The B/A ratio of >0.90 and the potential slagging temperature of <1150°C (Table 6), derived from the ash analyses and ash fusion data of the raw and washed Donkin parent coals, suggest that these coals will have a severe slagging tendency and should be burned in a wet bottom furnace.

FOULING INDICATORS

Most indices are applied by categorizing the coal as having an "eastern type" or "western type" ash. The term "western type" is defined as an ash having more (CaO + MgO) than Fe_2O_3, on a per cent weight basis. On the above basis, the ashes from the Donkin coals have (CaO + MgO):Fe_2O_3 ratios <1.0 and can be classified as "eastern type" ashes. This criterion depends solely on ash analyses and does not have any rank or geographic connotation.

There has been general agreement between research and operating practice that one of the dominant factors influencing superheater fouling is the sodium content of the coal ash. The following classification has been proposed:

Fouling category	% Na_2O in ash	
	"eastern type" ash $\frac{CaO + MgO}{Fe_2O_3}$ <1.0	"western type "ash $\frac{CaO + MgO}{Fe_2O_3}$ >1.0
Low	<0.5	<2.0
Medium	0.5 - 1.0	2.0 - 6.0
High	1.0 - 2.5	6.0 - 8.0
Severe	>2.5	>8.0

The Donkin coal ashes have a Na_2O content ranging from 0.6 to 1.5% (Table 3), which indicates that they are in the medium to high fouling category of the "eastern type" ash.

Another possible indication of the fouling potential of a coal is based on its ash content as outlined below:

Fouling potential	Ash content, wt %
Low	<15
Medium	15 - 25
High	>25

The raw and washed Donkin coals have ash contents of <15% (Table 2), indicating that they are in the low fouling category.

PILOT-SCALE RESEARCH BOILER

The CCRL pilot-scale research boiler is a pulverized coal-fired boiler incorporating two opposing low-swirl burners (Fig. 4). The furnace is U-shaped and consists of a vertical refractory shaft and a vertical steam boiler, which are connected at the bottom through a horizontal refractory tunnel. This boiler can be fired by the twin low-swirl burners located in four basic positions; known as the I, J, J_1 and U configurations. It is expected that highly reactive fuels will burn efficiently when fired in the I configuration. However, for fuels that are difficult to burn, residence times and combustion zone temperatures can be increased by locating the twin burners in the U configuration. Intermediate residence times, if required, can be obtained by locating the burners in the J or J_1 configurations. It is estimated that at full load and with the burners located in the I configuration, the combustion chamber residence time will be about one second. This residence time will increase to about three seconds with the burners located in the U configuration. The combustion chamber heat release rate is about 0.35 $MJ/s/m^3$.

All of the sections of the furnace are designed to operate at pressures up to 2.5 kPa (250 mm of water). At the full-load firing rate of 2.5 GJ/h (0.7 MW), the boiler generates about 730 kg/h of steam at 690 kPa.

It is possible to control the furnace exit temperature by adding cooled-wall panels in the refractory shaft or by partially insulating the water walls of the boiler.

Crushed coal is supplied to the furnace from a 4500-kg hopper, mounted on an electronic weigh scale, through a variable-speed worm feeder to a ring-and-roller type of pulverizer, which is normally swept and pressurized by air up to 230°C. If necessary, the pulverizer can be swept and pressurized with a mixture of air and flue gas up to 400°C. The pulverizer contains a motor-driven classifier for controlling coal fineness and a riffle at the pulverizer outlet proportions the coal to each burner. Secondary air can be supplied to the burner up to 260°C.

Combustion gases leave the furnace between 900-1300°C, then pass through a transition section, a test-air heater and a conventional three-pass air heater before entering a long horizontal sampling duct. A bypass from the air heater to the stack breeching and an additional heat exchanger surface in the sampling duct permit the gas temperature in the sampling duct to be varied from 150°C to 300°C.

A forced-draft fan supplies air to the air heater at 7 kPa (71 cm WC). The air, on leaving the heater, is divided into three systems: primary air to the pulverizer, secondary air to the burners and cooling air to the test air heater. The last stream, after leaving the test-air heater, can either be exhausted to the atmosphere or blended with the primary air supply to the pulverizer.

The research boiler is manually controlled, except for electrical interlocks to ensure that safe startup and shutdown procedures are followed. When burning high-grade coals, it has been possible to operate with as little as 1.0% O_2 and less than 100 ppm CO in the flue gases, with a smoke density of less than No. 1 Ringlemann.

EXPERIMENTAL PROCEDURES

OPERATING PROCEDURE

The following procedure, with minor variations in timing, was used for all trials:

1. Before each test, all boiler and air heater fireside surfaces were thoroughly cleaned by air lancing and the furnace bottom was lined with a refractory blanket. Sufficient coal was bunkered to provide 7 h continuous operation.
2. At 0800 h, the cold boiler was preheated with No. 2 fuel oil fired at 10 g/h, using two oil torches. Excess air was adjusted to provide 5% O_2 in the flue gas and the boiler was allowed to stabilize at full steaming rate and pressure. All continuous monitoring instruments were activated.
3. At 0920 h, pulverized coal was fed to the boiler at a specified classifier speed, mill temperature and excess air level. One oil torch was left in operation.
4. After flame stability was established, the oil torch was removed, allowing the boiler to operate on pulverized coal only.
5. At 1100 h, scheduled testing was begun. Boiler panel readings were monitored continuously and recorded every half hour. A specified coal feed rate, coal fineness and excess air level were maintained as closely as possible for the test duration.
6. By 1600 h, all measurements were completed and the boiler was shut down.
7. The furnace was allowed to cool overnight. The furnace bottom was then removed, the duct works were dismantled and the ash in the furnace bottom and duct work were photographed, collected, weighed and sampled.

PARAMETERS OF COMBUSTION PERFORMANCE

The following combustion performance parameters were measured at the sampling stations illustrated in Fig. 4:

1. Coal quality of a composite sample was taken from the crushed coal feed at the pulverizer inlet. Station 1.
2. Moisture and sieve analyses of pulverized coal samples were taken at the pulverizer outlet. Station 2.
3. O_2 content of the flue gas was measured continuously by a Dynatron oxygen analyzer and a paramagnetic monitor. Stations 8 and 10, respectively.

4. NO content of the flue gas was measured continuously by a chemiluminescent monitor. Station 10.
5. CO and CO_2 contents of the flue gas were measured continuously by infrared monitor. Station 10.
6. SO_2 and SO_3 contents of the flue gas were measured continuously by ultra-violet and absorption colorimetric methods. Stations 10 and 13, respectively.
7. Low-temperature corrosion potential was measured by three mild steel probes which were inserted simultaneously into the flue gas stream and maintained at three different temperatures for the duration of the combustion test. Station 9.
8. Fly-ash loading was measured by an isokinetic sampling system, three samples per test. These samples were analyzed for carbon content and dust loading. Stations 15 and 16.
9. Aerodynamic size distribution was determined in a fractionating sampler and in a Cascade cyclone sampler. Station 12.
10. Fouling of heat-transfer surfaces was evaluated by visual examination and chemical composition of ash build-up on a simulated superheater, installed immediately downstream of the screen tubes. Station 7.
11. Slagging propensity was determined by examining the thickness, physical structure, chemical composition and melting characteristics of ash deposits selected from various parts of the furnace. Stations 3 to 6.
12. Fly-ash resistivities were measured by an in situ, point-plane resistivity apparatus at flue gas temperatures of approximately 300°C at Station 11, and 180°C at Station 14.

COMBUSTION PERFORMANCE

COAL COMMINUTION

The Donkin coals were crushed, dried, metered and pulverized to the selected degree of fineness without difficulty. The CCRL coal drying and grinding system is illustrated in Fig. 5. The pulverized coals were then transported directly to the burners without moisture separation from the carrying air. The size distribution of the pulverized coals for each of the trials is shown in Tables 7 and 8. A coarse grind (72 to 76% minus 200 mesh)

was maintained for the trials (C-1A to C-5A) in Table 7, while a finer grind (80% to 89% minus 200 mesh) was maintained for the trials (C-1B to C-5B) in Table 8.

BOILER OPERATION AND FLAME CHARACTERISTICS

The boiler operating conditions, shown in Tables 7 and 8, remained essentially constant between 2100 and 2300 MJ/h input for all furnace trials. The flame was bright, clean and stable under reasonably steady-state conditions and an oil support flame was required for only a few minutes at the start of each trial. It should be noted that the coals were fired in the I configuration for all of the furnace trials.

GASEOUS EMISSIONS

The average flue gas analyses for each combustion trial are summarized in Tables 7 and 8. The carbon monoxide levels, at less than 100 ppm, do not constitute either an emission problem or a significant thermal penalty.

The uncontrolled sulphur dioxide emissions from the Donkin coal samples were 1.0 to 1.6 g SO_2/MJ, which is much higher than the current Canadian national emission guideline of 0.258 g SO_2/MJ of fuel input for new combustion systems (5). The nitrogen oxide emission rates of 0.32 to 0.41 g NO/MJ are well above the current Canadian national emission guideline of 0.168 g NO/MJ of fuel input, but this level is specific to the CCRL combustion equipment and it can be significantly improved through the use of modern low-NO_x burner technology.

FLY ASH CHARACTERISTICS AND COAL BURN-OUT

The mass loadings, aerodynamic particle size and combustible content of the fly ash for each trial are summarized in Tables 9 and 10. The fly ash loadings are generally higher for the coals containing a greater percentage of ash, but it is evident that the washed coal sample containing the least amount of ash (1.9%) had a fly ash loading noticeably greater than either of the other washed products. It is not clear why this was the case, but it may be related to the apparently higher calcium oxide content of the fly ash (Tables 11 and 12). It is also clearly evident that in each case the more finely ground coal resulted in a lower combustible content in the fly ash.

In general, high electrical resistivity (>10 log ohm-cm) indicates that precipitated fly ash will retain a strong electrical charge and repel any similarly charged particles or generate a back corona within the deposit; precipitation, conversely, is therefore difficult. A low resistivity (<7 log ohm-cm) fly ash will readily precipitate but will not adhere strongly to the collecting plates and will easily be re-entrained in the flue gas. Intermediate resistivity values of approximately 8 to 9 log ohm-cm are considered to yield the best precipitator efficiencies.

The measured in situ electrical resistivity of the fly ash from each of the trials, at either the high or low temperature, was approximately 5 log ohm-cm (Tables 9 and 10). There did not appear to be any significant difference in these values that could be attributed to the ash content of the coal samples. They suggest that the operating efficiency of an electrostatic precipitator will be the same for the washed coals as would be obtained with the raw Donkin coal.

ASH SLAGGING AND FOULING

The calculated potential slagging temperature and the base/acid ratio shown in Table 6 indicate a high-to-severe slagging propensity for the Donkin coal samples compared with the medium propensity of the reference coal. This severe slagging of the Donkin coal samples, which was not noticeably affected by cleaning, was confirmed by the combustion trials (Fig. 6 and 7). The analytical data on the furnace products collected from the combustion trials are tabulated in Tables 13 to 18. The calculated slagging potentials of these products, shown in Tables 19 to 22, also confirm the predicted severe slagging potential of the Donkin coals. The analytical data on the parent coal ashes predicted a low fouling tendency which was confirmed by the powdery, loosely adherent deposits formed on the water walls and the convective heat transfer surfaces (Fig. 8 and 9). The 70% reduction in the ash content of the coal appeared to reduce the amount of slag formed in the furnace bottom (Fig. 7). However, there was little noticeable change in the small amount of ash that collected on the superheater tubes (Fig. 9). There were no material changes to the furnace operating temperatures (Tables 7 and 8) that could be attributed to the reduction in ash content of the coal.

CONCLUSIONS

The Donkin coals handled and flowed without difficulty. The resulting ground coal product ignited readily to produce stable combustion flames. These flames appeared similar to each other and to those of the reference thermal coal.

The petrographic data and coal analyses suggested that the carbon burn-out from the Donkin coals (raw and washed) should be favourable but thermogravimetric analyses suggested that the combustion reactivity of these coals would be lower than that of the reference coal. Combustion studies in the utility boiler indicated that the raw Donkin coal can be burned to about 28% combustible content in the fly ash with a fine grind (88% minus 200 mesh) while the fly ash from the finely ground washed coals contained from 34 to 43% combustible content, giving combustion efficiencies ranging from 97 to 99%. These figures compare to a 2% combustible content in the fly ash from the thermal reference coal, containing 10.5% ash and fired at a grind of 89% minus 200 mesh, to give a 99.7% combustion efficiency (higher than any of the Donkin coal samples). However, as reported earlier (1), increasing the residence time in the combustion chamber to about two seconds can decrease the combustible content in the fly ash to about 2%, giving combustion efficiencies higher than that achieved with the reference coal. The reduction in ash content of the coal did not appear to affect the overall furnace operating temperatures or the severity of the coal ash to slag.

Washing the Donkin coal reduced the sulphur content of the coal from 3.0% to 1.7%, depending on the amount of ash removed. The overall reduction in SO_2 evolved in the flue gas (g/MJ of fuel input) compared with the raw coal varied from 15% to 35% with the higher SO_2 reduction occurring with the higher ash removal. However, the lowest emission rate of 1.053 g SO_2/MJ is still well above the current Canadian emission guideline of 0.258 g SO_2/MJ of fuel input.

The tendency of the coal ash to slag was predicted to be severe from the analytical data on the parent Donkin raw and washed coal samples. This prediction was confirmed by the fluid slag produced in the refractory-lined furnace bottom. The analytical data on the parent coals also indicated a low fouling tendency, which was consistent with the powdery, easily removed ash material deposited on the water-walls and the superheater tubes during the combustion trials.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the efforts of B.C. Post, pilot-plant supervisor, and the staff of the Industrial Combustion Processes Section during the coal combustion evaluation experiments. In addition, thanks are due to our petrographer J.C. Jorgensen, as well as the staff of the Analysis and Standardization Section of the Energy Research Laboratories who provided invaluable petrographic and analytical support services.

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Table 1 - Screen analysis of coal head samples

Screen size (mm)	Weight % (cumulative)				
	Reference coal	Raw(1) Donkin coal	Donkin Washed coals		
			No. 2	No. 7	No. 8 & 9
+25.4	1.75	7.61	-	-	-
+19.1	3.70	12.60	-	-	-
+12.7	9.84	22.43	0.38	0.20	0.22
+6.4	28.86	44.01	8.92	0.64	2.36
+3.2	54.32	65.18	44.25	37 11	18.20
-3.2	45.68	34.82	55.75	62.89	81.80
Bulk density (kg/m^3)	881	733	631	607	575
Moisture wt %	8.4	8.0	6.3	7.3	9.7

Table 2 - Coal analyses

Component	Analyses					Pacific Rim Specifications	
	Ref. coal	Raw(1) Donkin coal	Washed Donkin coal				
			No. 2	No. 7	No. 8 & 9		
	C-1	C-2	C-3	C-4	C-5	KECO	EPDC
Moisture, wt %							
As received	6.04	1.91	6.82	6.16	6.91	<15	<10
Equilibrium	8.72	2.88	3.24	3.21	3.13	-	-
Proximate, wt % (dry)							
Ash	10.50	7.02	3.94	2.14	1.91	<17	<20
Volatile matter	33.39	36.03	39.69	37.55	36.96	22-36	$\frac{VM}{FC} \geq 0.4$
Fixed carbon	56.11	56.95	59.37	60.31	61.13	50-60	
Ultimate, wt %							
Carbon	71.04	77.98	81.44	83.35	83.42	-	-
Hydrogen	4.46	5.10	5.11	5.25	5.27	-	-
Sulphur	0.22	3.04	2.41	1.73	1.70	<1.0	<1.0
Nitrogen	1.16	1.62	1.56	1.50	1.53	<2.0	<1.8
Ash	10.50	7.02	3.94	2.14	1.91	-	-
Oxygen (by diff)	12.62	5.24	5.54	6.03	6.17	-	-
Sulphur Forms							
Sulphate	0.00	0.08	0.26	0.07	0.08	-	-
Pyritic.....	0.07	1.78	0.88	0.42	0.43	-	-
Organic	0.15	1.18	1.27	1.24	1.19	-	-
Calorific value, MJ/kg	28.20	32.34	33.65	34.50	34.52	>25.12	>25.12
Hardgrove grindability index	52	62	61	62	61	>45	>45
Chlorine in coal, wt %	<0.01	0.09	0.13	0.14	0.17	-	-
Free swelling index	N.A.*	7.5	7.5	8.0	8.0	-	-
Ash Fusibility, °C							
Reducing atmosphere							
Initial deformation	1218	1066	1068	1071	1077	>1250	-
Spherical deformation	1313	1107	1093	1124	1127	-	-
Hemispherical deformation.	1391	1229	1146	1188	1213	-	-
Fluid temperature	1454	1254	1260	1285	1346	-	-
Oxidizing atmosphere							
Initial deformation	1266	1329	1374	1385	1388	-	-
Spherical deformation	1377	1402	1402	1404	1421		>1200
Hemispherical deformation.	1424	1412	1407	1413	1426	-	-
Fluid temperature	1479	1418	1418	1418	1432	-	>1300

*Non-agglomerating

Table 3 - Analyses of parent coal ash

Major elemental oxides (wt %)	Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
	C-1	C-2	C-3	C-4	C-5
SiO_2	60.01	30.60	27.79	25.63	25.87
Al_2O_3	18.09	16.40	18.14	18.23	18.51
Fe_2O_3	3.60	35.25	45.43	46.63	44.84
TiO_2	0.86	0.89	0.94	1.04	1.06
P_2O_5	0.25	0.16	0.10	0.11	0.17
CaO	7.85	5.64	2.05	1.94	2.21
MgO	1.59	0.54	0.42	0.42	0.49
SO_3	3.90	5.18	1.58	1.41	2.47
Na_2O	1.35	0.73	0.59	0.79	1.47
K_2O	0.41	0.98	1.01	0.87	0.95
BaO	0.15	-	-	0.12	0.36
SrO	0.11	-	0.01	0.01	0.03
L.O.F.	0.81	1.65	0.47	0.37	0.68

Table 4 - Trace elements determined in coal samples (ppm)

Element	Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
	C-1	C-2	C-3	C-4	C-5
Antimony (Sb).....	0.7	0.7	<1	<1	<1
Arsenic (As)	3.1	22	15	7	6
Barium (Ba)	265	34	<100	<100	<100
Bromine (Br)	0.4	28	26	27	27
Caesium (Cs)	0.4	0.4	<1	<1	<1
Cerium (Ce)	14	8.7	<100	<100	<100
Chlorine (Cl)	29	1350	1400	1400	1500
Chromium (Cr)	5.4	7.5	<100	<100	<100
Cobalt (Co)	1.7	2.5	3	2	2
Copper (Cu)	8.7	8.1	<100	<100	<100
Dysprosium (Dy)	1.1	0.7	0.5	0.3	0.4
Europium (Eu)	0.2	<0.2	0.1	3.0	0.1
Hafnium (Hf)	1.1	<0.5	<1	<1	<1
Holmium (Ho)	0.2	<0.5	<1	<1	<1
Iodine (I)	<0.5	1.3	1	1	1
Lanthanum (La)	6.5	4.1	4	3	2
Lutecium (Lu)	0.1	<0.1	<0.1	<0.1	<0.1
Manganese (Mn)	31	45	20	15	12
Mercury (Hg)	<0.3	<0.6	-	-	-
Molybdenum (Mo)	2.1	4.7	<10	<10	<10
Neodymium (Nd)	4.7	<2.7	<1000	<1000	<1000
Nickel (Ni)	<26	<36	<100	<100	<100
Rubidium (Rb)	<4.3	<6.2	<10	<10	<10
Samarium (Sm)	1.1	0.7	0.6	0.4	0.4
Scandium (Sc)	1.7	1.3	1.1	0.7	0.7
Strontium (Sr)	130	43	<100	<100	<100
Tantalum (Ta)	0.2	0.1	<1	<1	<1
Thorium (Th)	2.5	0.9	<10	<10	<10
Uranium (U)	1.4	0.3	<1	<1	<1
Vanadium (V)	10.5	3.9	9	6	6
Zinc (Zn)	<10	<11	<100	<100	<100

Table 5 - Petrographic examination of coal macerals

Maceral form	Volume %				
	Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
	C-1	C-2	C-3	C-4	C-5
Reactives					
Exinite	3.9	4.7	4.8	5.4	4.3
Vitrinite	64.8	80.1	82.4	81.2	84.6
Reactive semi-fusinite	5.5	1.7	2.0	2.2	1.8
Sub-total	74.2	86.5	89.2	88.8	90.7
Inerts					
Fusinite	6.5	3.1	2.0	2.9	1.8
Semi-fusinite	11.0	3.4	4.0	4.4	3.5
Micrinite	2.4	2.4	2.1	2.3	2.6
Mineral matter	5.9	4.6	2.7	1.6	1.4
Sub-total	25.8	13.5	10.8	11.2	9.3
Mean Reflectance	0.60	0.86	0.88	0.88	0.91

Table 6 - Comparative indices of slagging potential - parent coal ashes

Slagging propensity	Reference limits	Ref. coal	Raw(1) Donkin coal	Washed Donkin coals		
		C-1	C-2	C-3	C-4	C-5
Base/Acid (B/A) Ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15 - 0.30	0.19	-	-	-	-
High	0.27 - 0.50	-	-	-	-	-
Severe	>0.50	-	0.9	1.06	1.13	1.10
Potential slagging temp, (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340 - 1230	1259	-	-	-	-
High	1230 - 1150	-	-	-	-	-
Severe	<1150	-	1135	1136	1139	1149

Table 7 - Boiler operating conditions (coarse grind)

Components	Reference coals	Raw(1) Donkin coal	Washed Donkin coals		
	C-1A	C-2A	C-3A	C-4A	C-5A
Furnace configuration	I	I	I	I	I
Fuel rate, kg/h	75.0	66.7	64.9	64.8	63.1
Fuel moisture, wt %	0.4	0.0	0.0	0.0	0.00
Coal fineness, wt % (Cdn std)					
+100 mesh	<1	<1	1	1	1
-100 + 140 mesh	5	6	6	6	9
-100 + 200 mesh	22	17	19	19	18
-200 + 325 mesh	48	51	50	57	48
-325 + 400 mesh	10	14	5	5	3
-400 mesh	14	11	19	21	21
-200 mesh	72	76	74	74	72
Heat input, MJ/h	2107	2157	2184	2236	2178
Furnace exit temp, °C	1000	904	1058	1032	1040
Air temperature, °C					
Pulverizer in	209	214	202	200	206
Pulverizer out	111	129	118	110	120
Secondary	268	255	239	253	242
Steam rate, kg/MJ	0.209	0.203	0.202	0.197	0.206
Flue gas rate, Nm^3/MJ	0.306	0.307	0.305	0.304	0.302
Flue gas analyses, volume					
CO_2 %	14.9	14.6	14.5	14.4	14.4
O_2 %	4.0	4.0	4.0	4.0	3.9
CO ppm	43	113	73	59	68
NO ppm	833	810	836	912	789
SO_2 ppm	220	1855	1591	1213	1425
SO_3 ppm	-	-	1.1	-	0.4
Emission rates, g/MJ					
NO	0.341	0.333	0.342	0.371	0.319
SO_2	0.192	1.628	1.389	1.053	1.230

Table 8 - Boiler operating conditions (fine grind)

Components	Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
	C-1B	C-2B	C-3B	C-4B	C-5B
Furnace configuration	I	I	I	I	I
Fuel rate, kg/h	74.5	66.0	61.8	66.1	63.1
Fuel moisture, wt %	0.0	0.0	0.0	0.0	0.0
Coal fineness, wt % (Cdn std)					
+100 mesh	<1	<1	1	1	1
-100 + 140 mesh	1	1	3	1	2
-140 + 200 mesh	9	11	13	8	14
-200 + 325 mesh	59	51	64	61	54
-325 + 400 mesh	14	20	4	7	5
-400 mesh	16	17	15	21	21
-200 mesh	89	88	83	89	80
Heat input, MJ/h	2101	2134	2080	2281	2178
Furnace exit temp, °C	1023	824	1040	1065	1048
Air temperature, °C					
Pulverizer in	212	212	212	212	204
Pulverizer out	119	126	126	123	113
Secondary	259	254	259	264	251
Steam rate, kg/MJ	0.198	0.200	0.213	0.191	0.205
Flue gas rate, Nm^3/MJ	0.306	0.307	0.305	0.304	0.304
Flue gas analyses, Volume					
CO_2 %	14.9	14.7	14.3	14.4	14.4
O_2 %	4.0	4.0	4.0	4.0	4.0
CO ppm	40	93	76	55	61
NO ppm	859	1004	889	930	806
SO_2 ppm	216	1625	1538	1210	-
SO_3 ppm	0.1	-	1.2	1.8	0.5
Emission rates, g/MJ					
NO	0.352	0.413	0.363	0.378	0.328
SO_2	0.189	1.426	1.343	1.051	-

Table 9 - Fly ash characteristics (coarse grind)

	Combustion trial				
	C-1A	C-2A(1)	C-3A	C-4A	C-5A
Precipitator inlet loading,					
g/Nm^3	2.50	2.62	1.84	1.12	2.06
g/MJ	0.76	0.80	0.56	0.34	0.62
Combustible content, wt %	6	34	41	54	53
Aerodynamic particle size, wt %					
+30 µm	-	-	-	-	-
+10 µm	53	34	25	21	26
+1 µm	98	85	80	86	80
Electrical resistivity, log ohm-cm					
@ 165°C - 175°C	7.7	5.5	4.7	4.6	4.5
@ 300°C - 360°C	5.3	5.6	5.2	5.3	5.3
Combustion efficiency, %*	99.20	96.16	97.26	97.54	97.89

*Combustion efficiency, $\% = 100 - \frac{33.727\ AC}{(100-C)\ Q}$

where: A = % ash in coal feed (dry basis)

C = % carbon in fly ash

Q = calorific value of coal feed, MJ/kg (dry basis)

Table 10 - Fly ash characteristics (fine grind)

	Combustion trial				
	C-1B	C-2B(1)	C-3B	C-4B	C-5B
Precipitator inlet loading,					
g/Nm^3	2.26	1.82	1.33	0.80	1.53
g/MJ	0.69	0.56	0.41	0.24	0.47
Combustible content, wt %	2	28	39	43	34
Aerodynamic particle size, wt %					
+30 µm	-	-	-	-	-
+10 µm	55	34	33	31	26
+1 µm	98	92	89	88	85
Electrical resistivity, log ohm-cm					
@ 165°C - 175°C	10.2	4.7	4.8	4.8	4.5
@ 300°C - 360°C	7.5	5.4	5.4	5.3	5.4
Combustion efficiency, %*	99.73	97.21	97.48	98.42	99.04

*Combustion efficiency, % = $100 - \frac{33.727\ AC}{(100-C)\ Q}$

where: A = % ash in coal feed (dry basis)

C = % carbon in fly ash

Q = Calorific value of coal feed, MJ/kg (dry basis)

Table 11 - Fly ash analyses (coarse grind)

Major elemental oxides (wt %)	Combustion trial				
	C-1A	C-2A(1)	C-3A	C-4A	C-5A
SiO_2	58.91	32.59	26.60	26.85	28.80
Al_2O_3	20.08	19.80	17.89	19.35	16.33
Fe_2O_3	4.27	33.72	46.82	44.03	43.27
TiO_2	1.11	0.92	1.01	1.33	1.05
P_2O_5	0.44	0.27	0.32	0.25	0.94
CaO	8.30	5.06	2.17	1.95	3.55
MgO	1.51	0.63	0.58	0.38	0.15
SO_3	0.45	3.08	0.21	2.22	1.18
Na_2O	1.46	0.76	1.34	0.91	1.78
K_2O	0.46	1.23	1.10	0.86	0.97
BaO	0.61	0.24	0.54	0.21	-
SrO	0.15	0.04	0.02	0.02	0.04

Table 12 - Fly ash analyses (fine grind)

Major elemental oxides (wt %)	Combustion trial				
	C-1B	C-2B(1)	C-3B	C-4B	C-5B
SiO_2	56.94	31.70	29.40	26.86	29.10
Al_2O_3	19.79	20.02	20.27	19.74	15.70
Fe_2O_3	4.51	34.25	44.87	44.80	44.34
TiO_2	1.13	0.91	1.19	1.38	1.00
P_2O_5	0.44	0.24	0.31	0.28	1.09
CaO	9.48	4.82	2.10	2.24	4.09
MgO	1.89	0.45	0.15	0.68	0.27
SO_3	0.73	2.79	0.84	1.01	1.66
Na_2O	1.23	0.81	1.19	1.96	1.09
K_2O	0.46	1.29	1.19	1.08	0.89
BaO	0.76	0.29	0.45	0.44	0.40
SrO	0.16	0.34	0.02	0.04	0.02

Table 13 - Trace elements determined in entrained fly ash (ppm)
(coarse grind)

Element	Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
	C-1A	C-2A	C-3A	C-4A	C-5A
Antimony (Sb)	14	9.5	14	10	21
Arsenic (As)	74	407	320	160	250
Barium (Ba)	4500	560	300	200	200
Bromine (Br)	5	63	28	45	25
Caesium (Cs)	4	4.2	5	3	4
Cerium (Ce)	100	89	100	100	<100
Chlorine (Cl)	<100	264	100	300	100
Chromium (Cr)	<100	95	100	300	100
Cobalt (Co)	26	28	30	26	30
Copper (Cu)	<100	105	100	100	100
Dysprosium (Dy)	12.4	7.0	6.8	6.8	5.8
Europium (Eu)	2.0	2.0	1.8	1.7	1.5
Hafnium (Hf)	13	3.2	3	2	2
Holmium (Ho)	2	9	1	1	1
Iodine (I)	2	3.4	2	2	<1
Lanthanum (La)	76	45	54	47	35
Lutecium (Lu)	1.5	0.6	0.6	3.2	0.4
Manganese (Mn)	340	429	400	330	320
Mercury (Hg)	-	<2	-	-	-
Molybdenum (Mo)	20	71	60	40	50
Neodymium (Nd)	<1000	35	<1000	<1000	<1000
Nickel (Ni)	<100	320	100	900	50
Rubidium (Rb)	30	53	40	<10	20
Samarium (Sm)	12.3	8.6	9.7	8.2	6.7
Scandium (Sc)	21.9	15	18.3	14.4	11.8
Strontium (Sr)	1000	547	300	200	200
Tantalum (Ta)	1	1.1	1	<1	<1
Thorium (Th)	30	11	10	10	10
Uranium (U)	18	3.7	4	3	3
Vanadium (V)	140	178	160	120	110
Zinc (Zn)	100	78	200	100	100

Table 14 - Trace elements determined in entrained fly ash (ppm)
(fine grind)

Element	Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
	C-1B	C-2B	C-3B	C-4B	C-5B
Antimony (Sb)	19	13	12	14	30
Arsenic (As)	100	438	260	190	410
Barium (Ba)	4500	370	300	300	300
Bromine (Br)	<1	45	27	53	15
Caesium (Cs)	5	5.3	4	3	4
Cerium (Ce)	100	111	100	100	100
Chlorine (Cl)	<100	120	100	500	<100
Chromium (Cr)	100	109	100	100	100
Cobalt (Co)	30	33	30	32	24
Copper (Cu)	<100	125	<100	100	100
Dysprosium (Dy)	12.3	8.4	7.9	8.0	6.9
Europium (Eu)	2.4	2.3	2.2	2.1	1.7
Hafnium (Hf)	<100	3.0	3	3	2
Holmium (Ho)	1	2.1	1	1	1
Iodine (I)	2	2.4	2	3	<1
Lanthanum (La)	86	56	60	56	41
Lutecium (Lu)	1.8	0.6	0.6	0.6	0.5
Manganese (Mn)	390	476	400	370	460
Mercury (Hg)	-	<1.9	-	-	-
Molybdenum (Mo)	40	85	50	50	80
Neodymium (Nd)	<1000	44	<1000	<1000	<1000
Nickel (Ni)	<100	<120	200	100	100
Rubidium (Rb)	30	53	50	30	20
Samarium (Sm)	13.5	10	10.4	10.4	8.4
Scandium (Sc)	25.3	18	19.1	18.6	14.1
Strontium (Sr)	1400	492	<100	200	200
Tantalum (Ta)	2	1.2	<1	1	1
Thorium (Th)	30	13	10	10	10
Uranium (U)	24	4.2	4	4	4
Vanadium (V)	160	202	160	160	130
Zinc (Zn)	200	89	100	200	100

Table 15 - Analyses of furnace bottom deposits (coarse grind)

	Combustion trial				
	C-1A	C-2A(1)	C-3A	C-4A	C-5A
Major elemental oxides (wt %)					
SiO_2	65.36	47.54	35.67	32.70	35.62
Al_2O_3	18.74	17.21	18.38	18.73	21.00
Fe_2O_3	3.89	24.56	37.46	43.87	36.50
TiO_2	0.67	0.57	0.80	0.80	0.92
P_2O_5	0.26	0.18	0.63	0.50	0.42
CaO	6.84	5.65	3.58	2.67	3.57
MgC	1.15	0.52	0.30	0.23	0.10
SO_3	0.43	-	-	0.47	0.42
Na_2O	0.54	0.41	0.19	0.24	0.34
K_2O	0.32	0.79	0.52	0.54	0.46
BaO	0.07	0.30	0.21	0.18	-
SrO	0.09	0.03	-	-	0.01
Ash fusibility, °C					
Reducing atmosphere					
Initial deformation	1260	1066	1071	1027	1049
Spherical softening	1293	1091	1088	1041	1099
Hemispherical deformation	1382	1193	1141	1077	1132
Fluid temperature	>1482	1346	1241	1318	1279
Oxidizing atmosphere					
Initial deformation	1263	1271	1338	1357	1354
Spherical softening	1363	1299	1388	1407	1404
Hemispherical deformation	1432	1379	1396	1413	1413
Fluid temperature	>1482	1416	1418	1424	1435

Table 16 - Analyses of furnace bottom deposits (fine grind)

	Combustion trial				
	C-1B	C-2B(1)	C-3B	C-4B	C-5B
Major elemental oxides (wt %)					
SiO_2	62.11	38.56	35.57	32.54	33.47
Al_2O_3	18.90	20.25	22.44	21.77	18.79
Fe_2O_3	4.60	31.81	34.36	39.03	41.94
TiO_2	0.63	0.70	0.98	0.88	0.81
P_2O_5	0.27	0.16	0.47	0.32	0.46
CaO	7.65	5.23	4.06	2.77	2.77
MgO	1.15	0.34	0.20	0.25	0.18
SO_3	0.34	-	0.29	0.34	0.37
Na_2O	0.51	0.43	0.28	0.27	0.09
K_2O	0.37	0.80	0.50	0.55	0.50
BaO	0.49	0.29	0.26	0.17	0.06
SrO	0.08	0.02	-	-	0.12
Ash fusibility, °C					
Reducing atmosphere					
Initial deformation	1254	1079	1102	1063	1029
Spherical softening	1299	1118	1143	1121	1049
Hemispherical deformation	1388	1210	1160	1210	1074
Fluid temperature	>1482	1310	1274	1321	1213
Oxidizing atmosphere					
Initial deformation	1268	1335	1329	1371	1363
Spherical softening	1335	1357	1407	1407	1407
Hemispherical deformation	1460	1371	1418	1421	1410
Fluid temperature	>1482	1396	1452	1424	1429

Table 17 - Analyses of superheater deposits (coarse grind)

	Combustion trial				
	C-1A	C-2A(1)	C-3A	C-4A	C-5A
Major elemental oxides (wt %)					
SiO_2	58.39	34.95	23.05	23.33	24.07
Al_2O_3	18.88	16.53	15.77	17.70	15.49
Fe_2O_3	4.67	32.09	52.67	51.49	49.97
TiO_2	1.01	0.82	0.83	1.04	0.89
P_2O_5	0.44	0.22	0.25	0.20	0.63
CaO	8.80	5.81	1.93	1.61	2.91
MgO	1.13	0.45	0.51	0.37	0.18
SO_3	1.65	3.19	1.00	2.09	2.47
Na_2O	1.50	0.41	0.60	1.09	0.78
K_2O	0.37	1.08	0.79	0.79	0.63
BaO	0.62	-	0.23	0.27	-
SrO	0.14	-	-	0.01	0.01
Ash fusibility, °C					
Reducing atmosphere					
Initial deformation	1232	1097	1096	1081	1063
Spherical softening	1285	1099	1118	1121	1079
Hemispherical deformation	1329	1102	1149	1174	1143
Fluid temperature	>1482	1186	1266	1302	1293
Oxidizing atmosphere					
Initial deformation	1277	1338	1382	1379	1363
Spherical softening	1335	1379	1443	1446	1432
Hemispherical deformation	1410	1400	1447	1449	1435
Fluid temperature	>1482	1416	1457	1452	1441

Table 18 - Analyses of superheater deposits (fine grind)

	Combustion trial				
	C-1B	C-2B(1)	C-3B	C-4B	C-5B
Major elemental oxides (wt %)					
SiO_2	59.45	27.20	23.41	23.12	24.06
Al_2O_3	20.16	15.39	16.29	17.02	14.25
Fe_2O_3	4.39	45.37	51.32	53.03	51.79
TiO_2	0.88	0.67	0.91	0.99	0.86
P_2O_5	0.31	0.14	0.16	0.17	0.71
CaO	9.94	4.65	1.69	1.82	3.15
MgO	1.38	-	0.48	0.40	0.39
SO_3	1.65	2.96	1.63	2.20	2.47
Na_2O	0.88	0.44	0.71	0.83	0.67
K_2O	0.30	0.86	0.82	0.78	0.67
BaO	0.47	-	-	0.31	0.34
SrO	0.12	0.01	-	-	-
Ash fusibility, °C					
Reducing atmosphere					
Initial deformation	1199	1068	1088	1096	1066
Spherical softening	1285	1074	1113	1132	1077
Hemispherical deformation	1360	1096	1146	1163	1088
Fluid temperature	1404	1316	1262	1232	1204
Oxidizing atmosphere					
Initial deformation	1252	1377	1368	1382	1374
Spherical softening	1329	1404	1452	1454	1441
Hemispherical deformation	1371	1410	1457	1460	1446
Fluid temperature	>1482	1418	1463	1466	1449

Table 19 - Comparative indices of slagging potential
- furnace bottom deposits (coarse grind)

Slagging propensity	Reference limits	Original ash source				
		Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
		C-1A	C-2A	C-3A	C-4A	C-5A
Base/Acid (B/A) Ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15 - 0.30	0.15	-	-	-	-
High	0.27 - 0.50	-	0.49	-	-	-
Severe	>0.50	-	-	0.77	0.91	0.71
Potential slagging temp (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340 - 1230	1294	-	-	-	-
High	1230 - 1150	-	-	-	-	-
Severe	<1150	-	1129	1136	1104	1122

Table 20 - Comparative indices of slagging potential
- furnace bottom deposits (fine grind)

Slagging propensity	Reference limits	Original ash source				
		Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
		C-1B	C-2B	C-3B	C-4B	C-5B
Base/Acid (B/A) Ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15 - 0.30	0.17	-	-	-	-
High	0.27 - 0.50	-	-	-	-	-
Severe	>0.50	-	0.65	0.67	0.78	0.86
Potential slagging temp (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340 - 1230	1295	-	-	-	-
High	1230 - 1150	-	-	1165	-	-
Severe	<1150	-	1137	-	1135	1105

Table 21 - Comparative indices of slagging potential
- superheater deposits (coarse grind)

Slagging propensity	Reference limits	Original ash source				
		Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
		C-1A	C-2A	C-3A	C-4A	C-5A
Base/Acid (B/A) Ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15 - 0.30	0.21	-	-	-	-
High	0.27 - 0.50	-	-	-	-	-
Severe	>0.50	-	0.76	1.42	1.32	1.35
Potential slagging temp (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340 - 1230	1268	-	-	-	-
High	1230 - 1150	-	1158	1166	1155	-
Severe	<1150	-	-	-	-	1137

Table 22 - Comparative indices of slagging potential
- superheater deposits (fine grind)

Slagging propensity	Reference limits	Original ash source				
		Reference coal	Raw(1) Donkin coal	Washed Donkin coals		
		C-1B	C-2B	C-3B	C-4B	C-5B
Base/Acid (B/A) Ratio						
Low	<0.15	-	-	-	-	-
Medium	0.15 - 0.30	0.21	-	-	-	-
High	0.27 - 0.50	-	-	-	-	-
Severe	>0.50	-	1.19	1.35	1.38	1.45
Potential slagging temp (Tps, °C)						
Low	>1340	-	-	-	-	-
Medium	1340 - 1230	1233	-	-	-	-
High	1230 - 1150	-	-	1162	1169	-
Severe	<1150	-	1136	-	-	1142

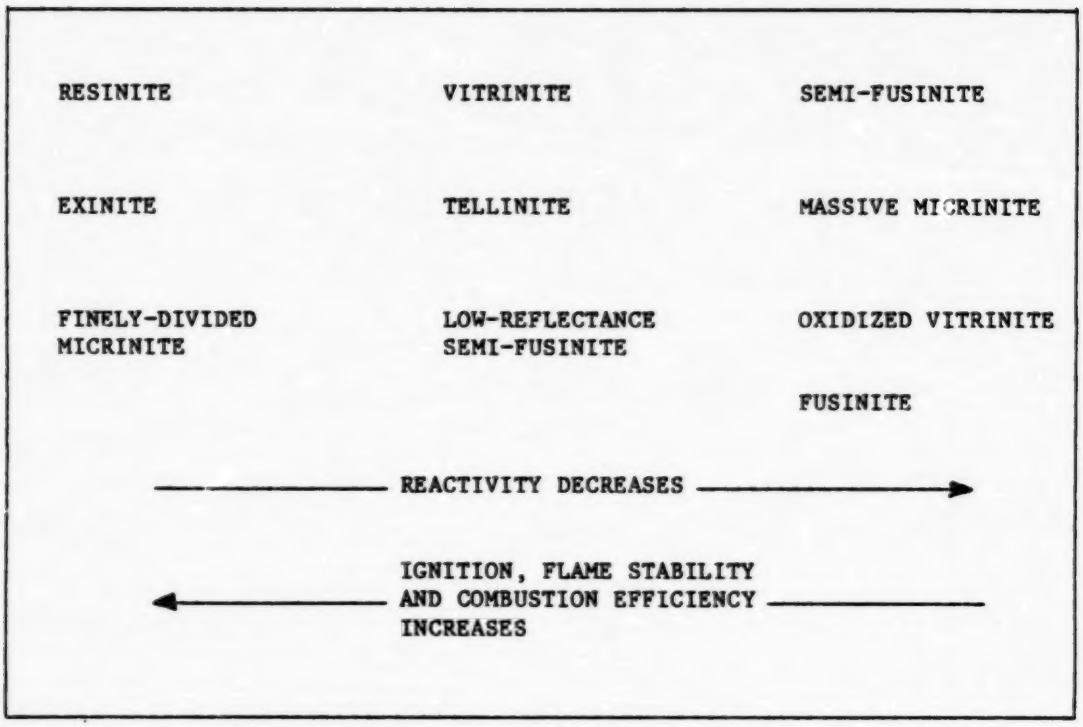


Fig. 1 - Influence of coal maceral type on combustion

CLASSIFICATION OF COAL BY RANK

Canada uses the systems and procedures of the American Society for Testing and Materials (ASTM) for sampling, analysing and classifying coals by rank, as detailed in the Annual Book of ASTM Standards. Basically coals are ranked according to their degree of metamorphism, or progressive alteration, in the natural series from lignite to anthracite.

Classification in the ASTM system is a function of fixed carbon content and calorific value calculated on the mineral-matter-free basis. The high rank coals are classed according to calorific value on the moist basis. The agglomerating characteristics of coals (i.e. their binding and/or swelling qualities when heated in the absence of oxygen) are used to differentiate between certain adjacent groups in the ranking.

VM%*	FC%*	CLASS	GROUP	CALORIFIC VALUE**	
				Btu per lb	Mj/kg
2	98	Anthracite(1)	Meta Anthracite		
8	92		Anthracite		
14	86		Semianthracite		
22	78	Bituminous(2)	Low Volatile Bituminous		
31	69		Medium Volatile Bituminous		
			High Volatile A Bituminous	14 000	32.6
			High Volatile B Bituminous	13 000	30.2
			High Volatile C Bituminous		
		Sub-bituminous(4)	Sub-bituminous A(3)	11 500	26.7
			Sub-bituminous B	10 500	24.4
			Sub-bituminous C	9 500	22.1
		Lignitic(4)	Lignite A	8 300	19.3
			Lignite B	6 300	14.7

* Dry, mineral-matter-free basis
**Moist, mineral-matter-free basis
(1) Non-agglomerating; if agglomerating classified as low volatile bituminous
(2) Commonly agglomerating
(3) If agglomerating classified as high volatile C bituminous
(4) Non agglomerating
VM: Volatile matter
FC: Fixed carbon

Source: Energy, Mines and Resources, Canada CANMET Report 83-20E

Fig. 2

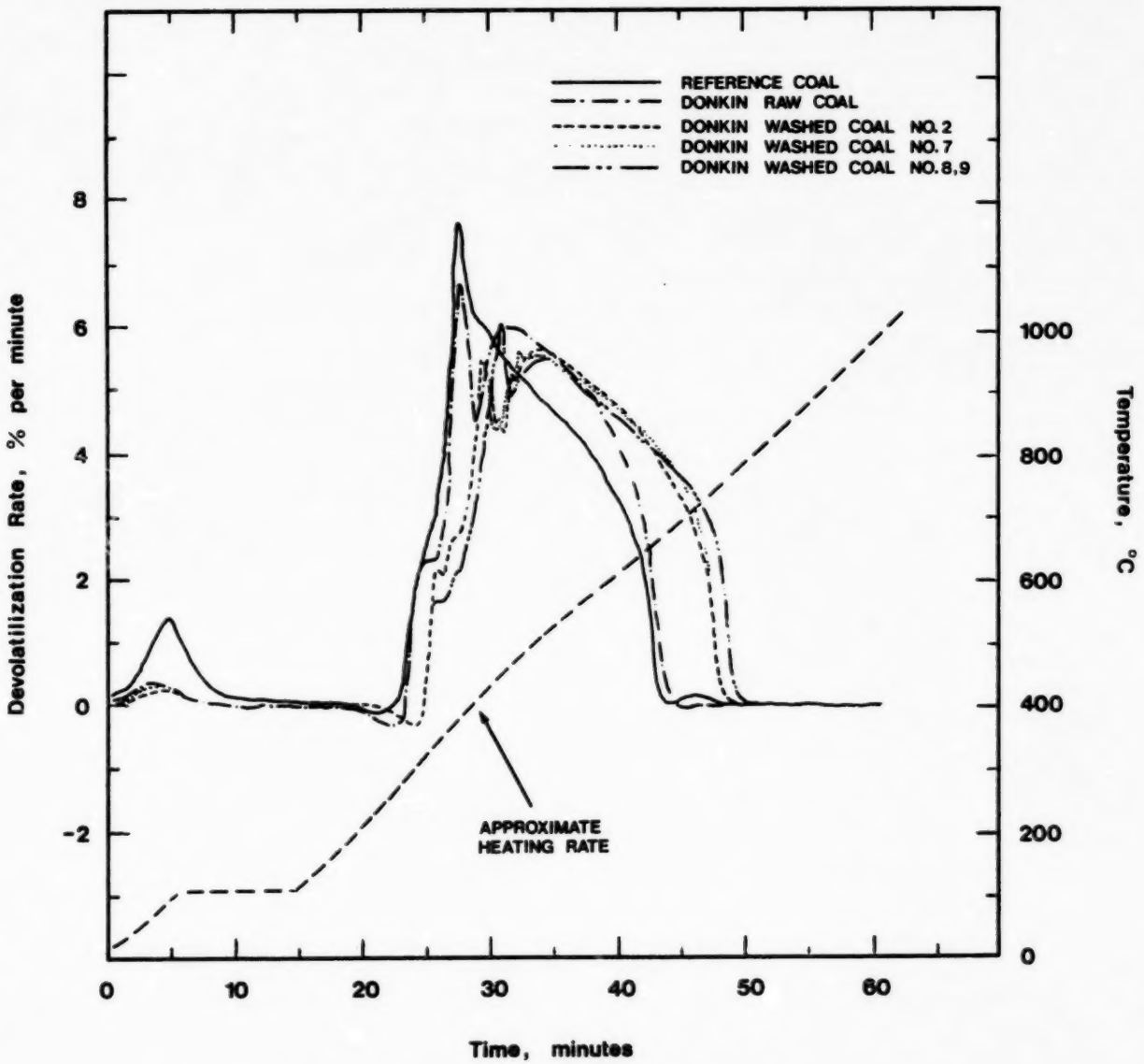


Fig. 3 - Comparative thermogravimetric analyses of Donkin mine coals and A thermal reference coal

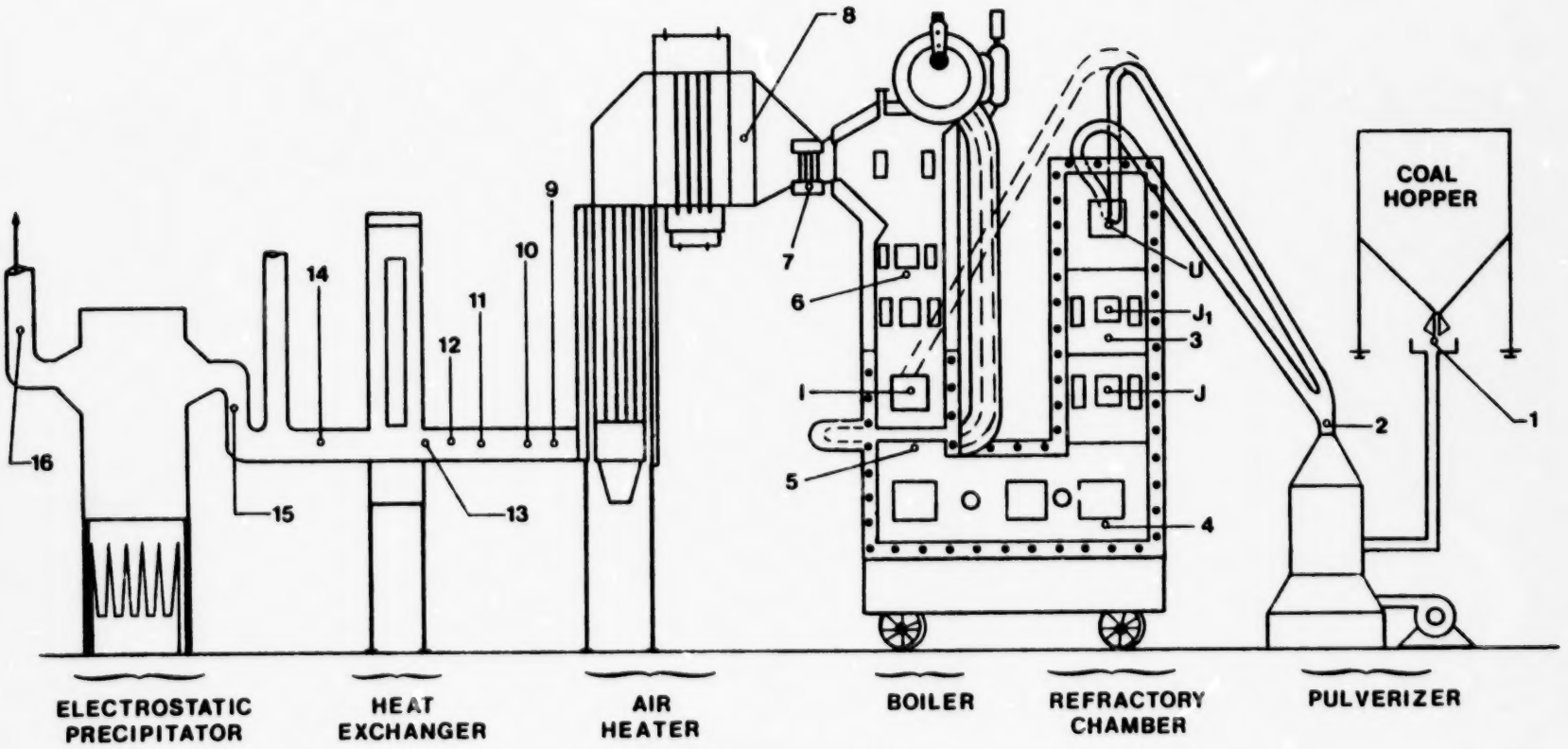


Fig. 4 - Schematic illustration of the CCRL pilot-scale boiler showing sampling stations

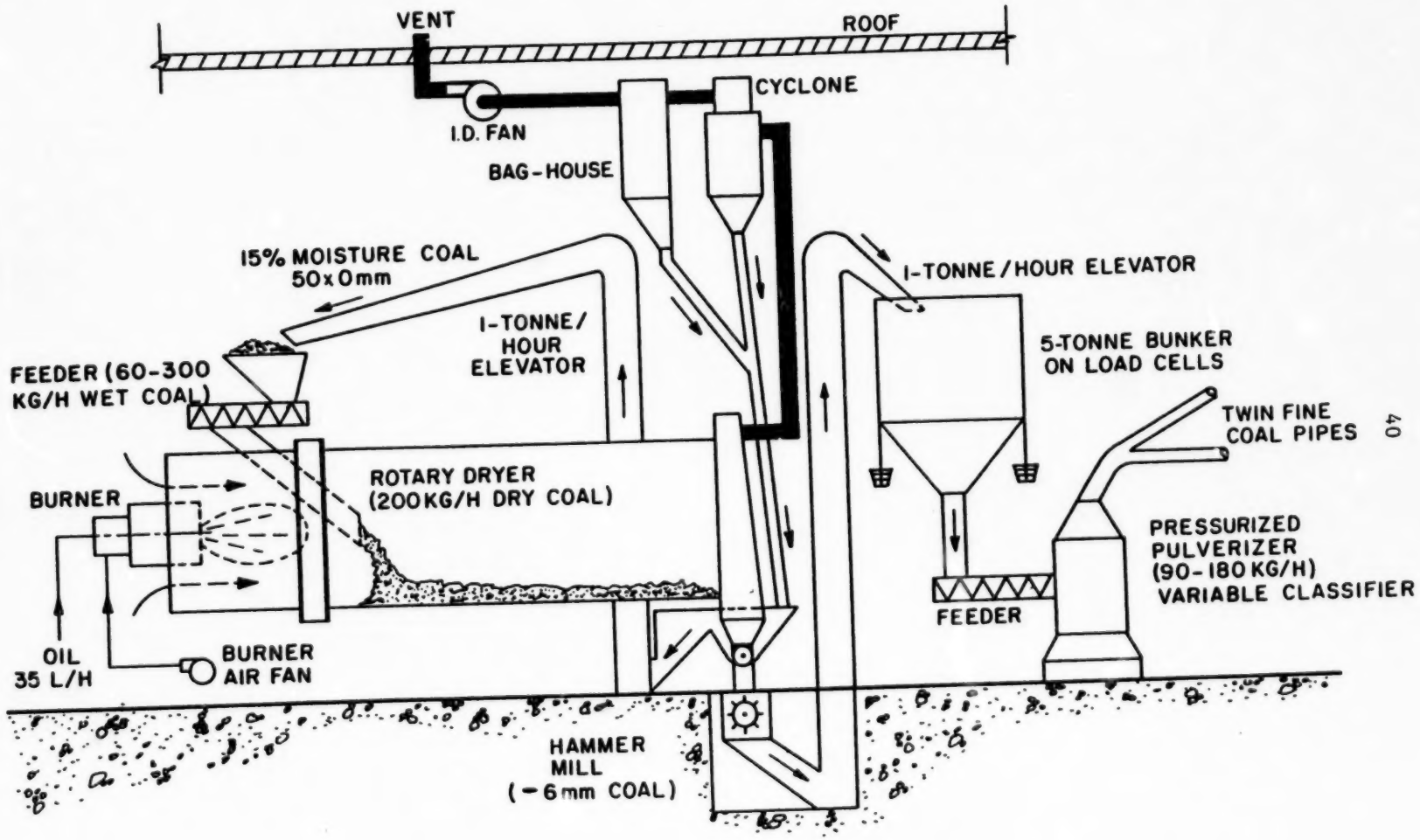
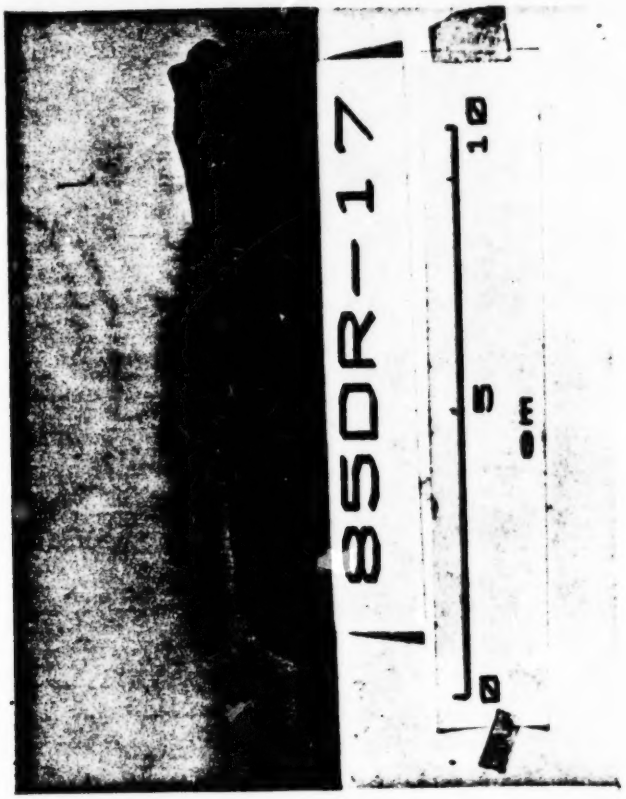
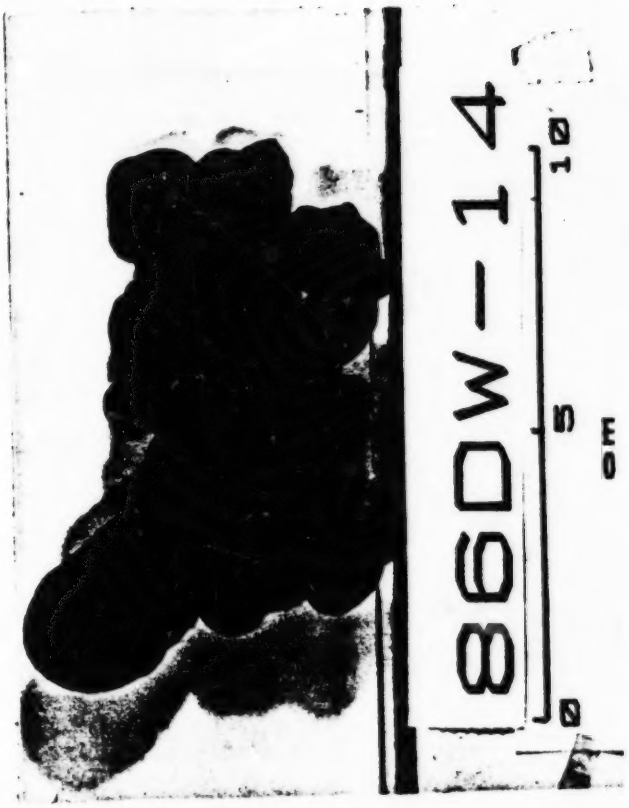


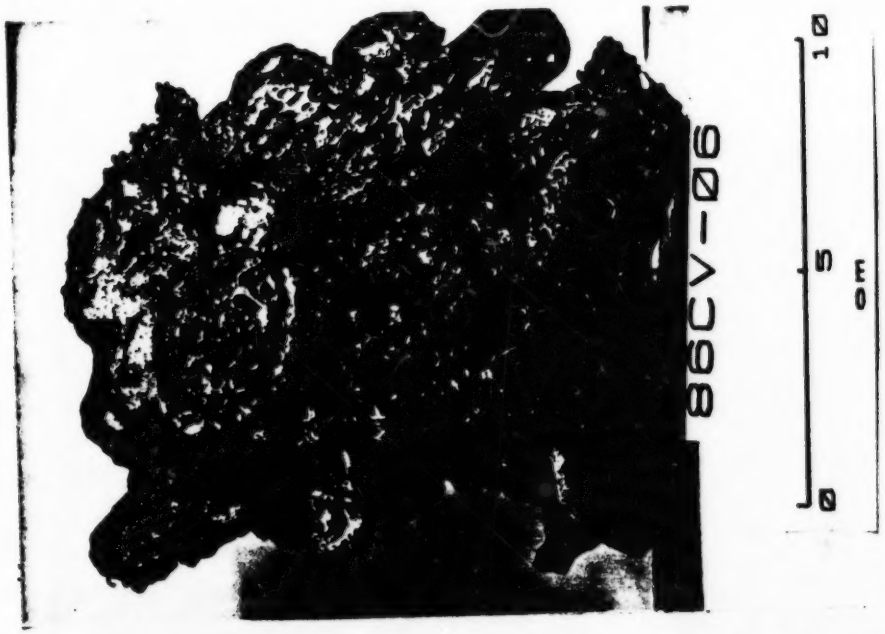
Fig. 5 - Schematic illustration of the CCRL solid fuel drying and grinding system.



Raw Donkin Coal (C-2)



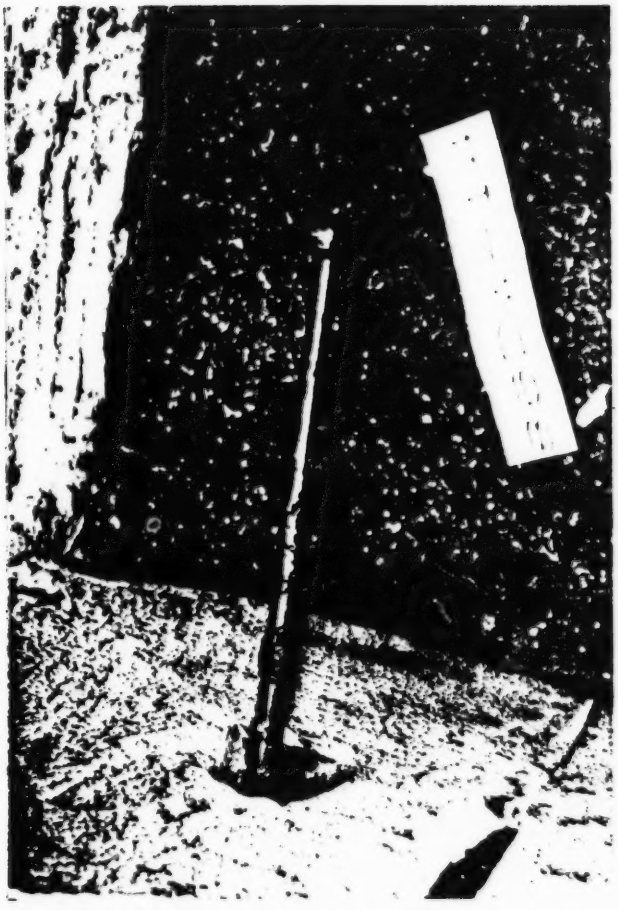
Washed Donkin Coal (C-4)



Reference Coal (C-1)

Fig. 6 - Cross-sectional photographs of furnace bottom deposits

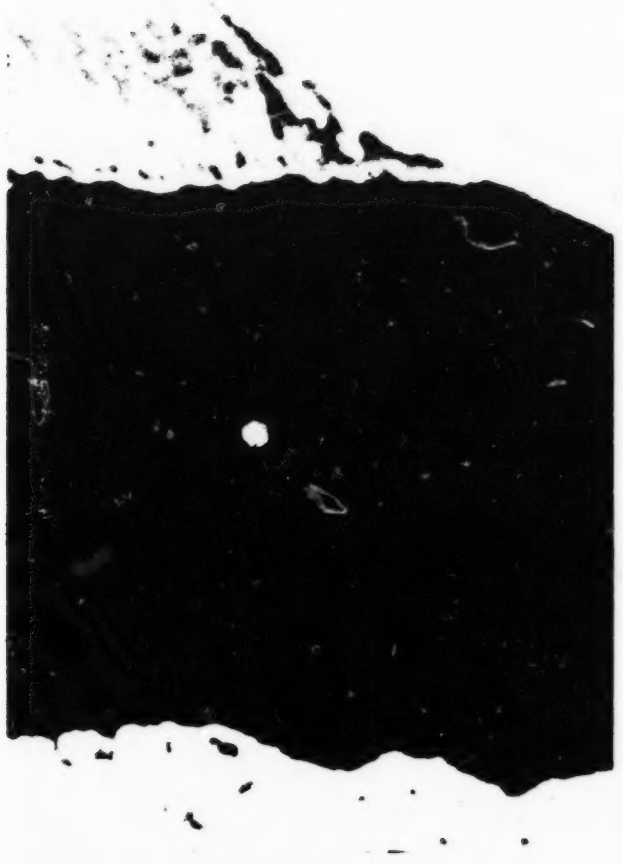
Raw Donkin coal (C-2)



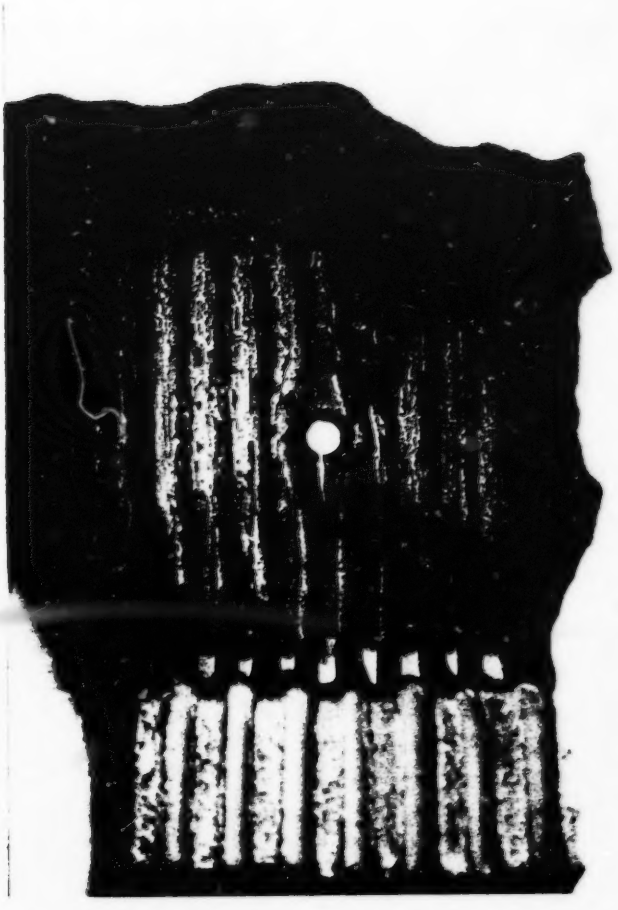
Washed Donkin coal (C-4)

Reference coal (C-1)

Fig. 7 - Deposits in furnace bottom



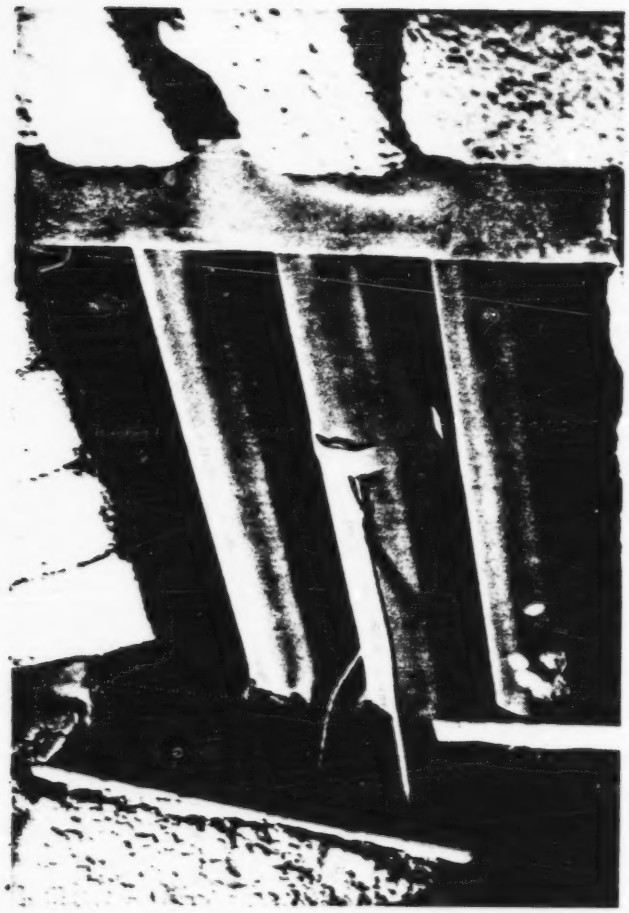
Raw Donkin coal (C-2)



Washed Donkin coal (C-4)

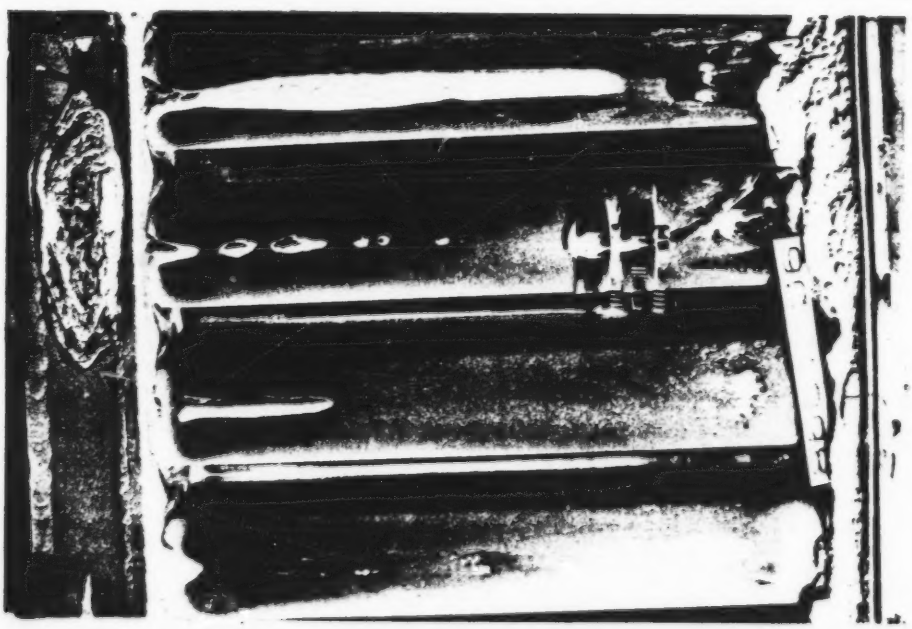
Reference coal (C-1)

Fig. 8 - Deposits on refractory and water-walls of furnace



Raw Donkin coal (C-2)

Washed Donkin coal (C-4)



Reference coal (C-1)

Fig. 9 - Deposits on superheater tubes

APPENDIX "A"

DONKIN COAL

COMBUSTION CHARTS

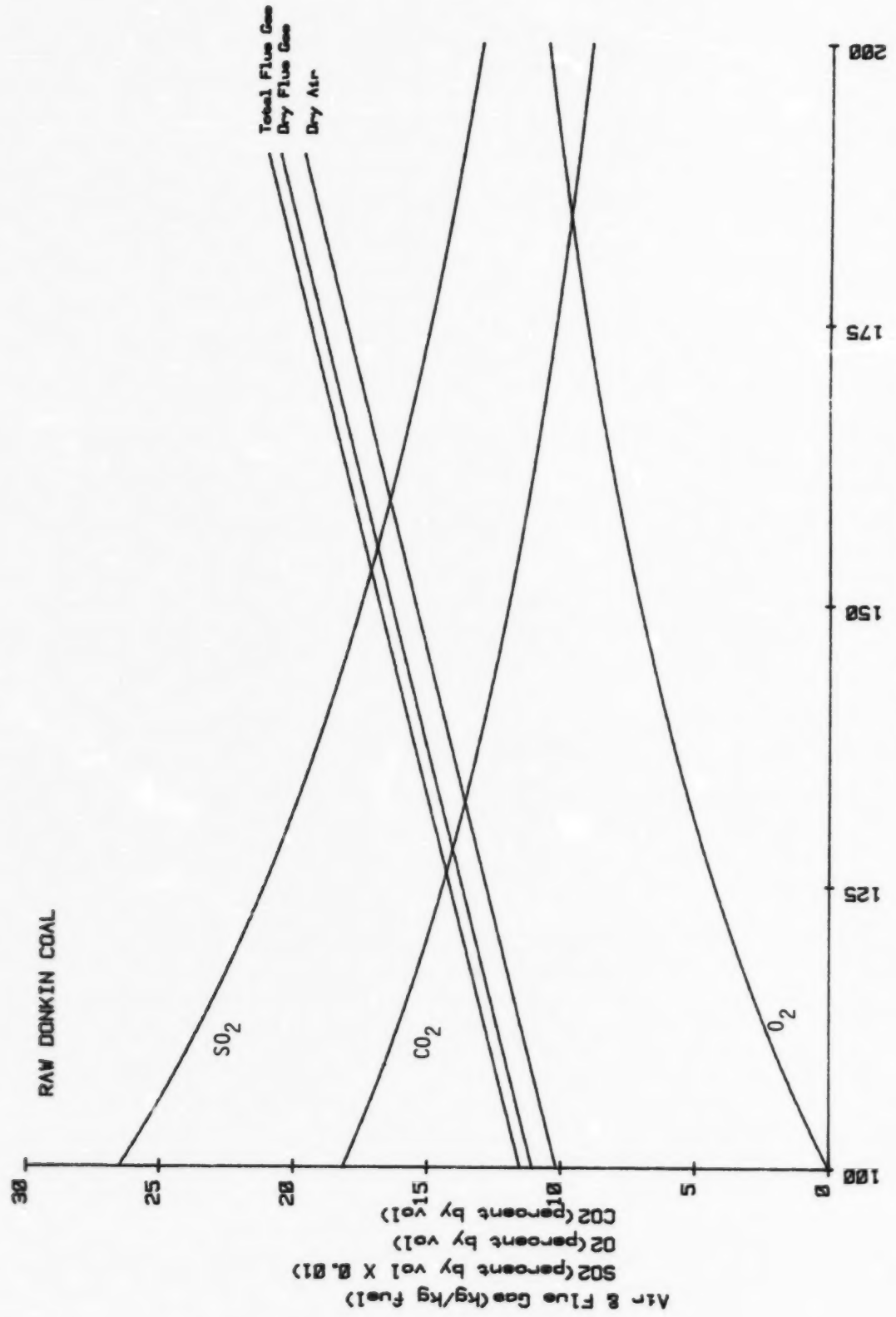


Fig. 1A - Combustion data, weight basis

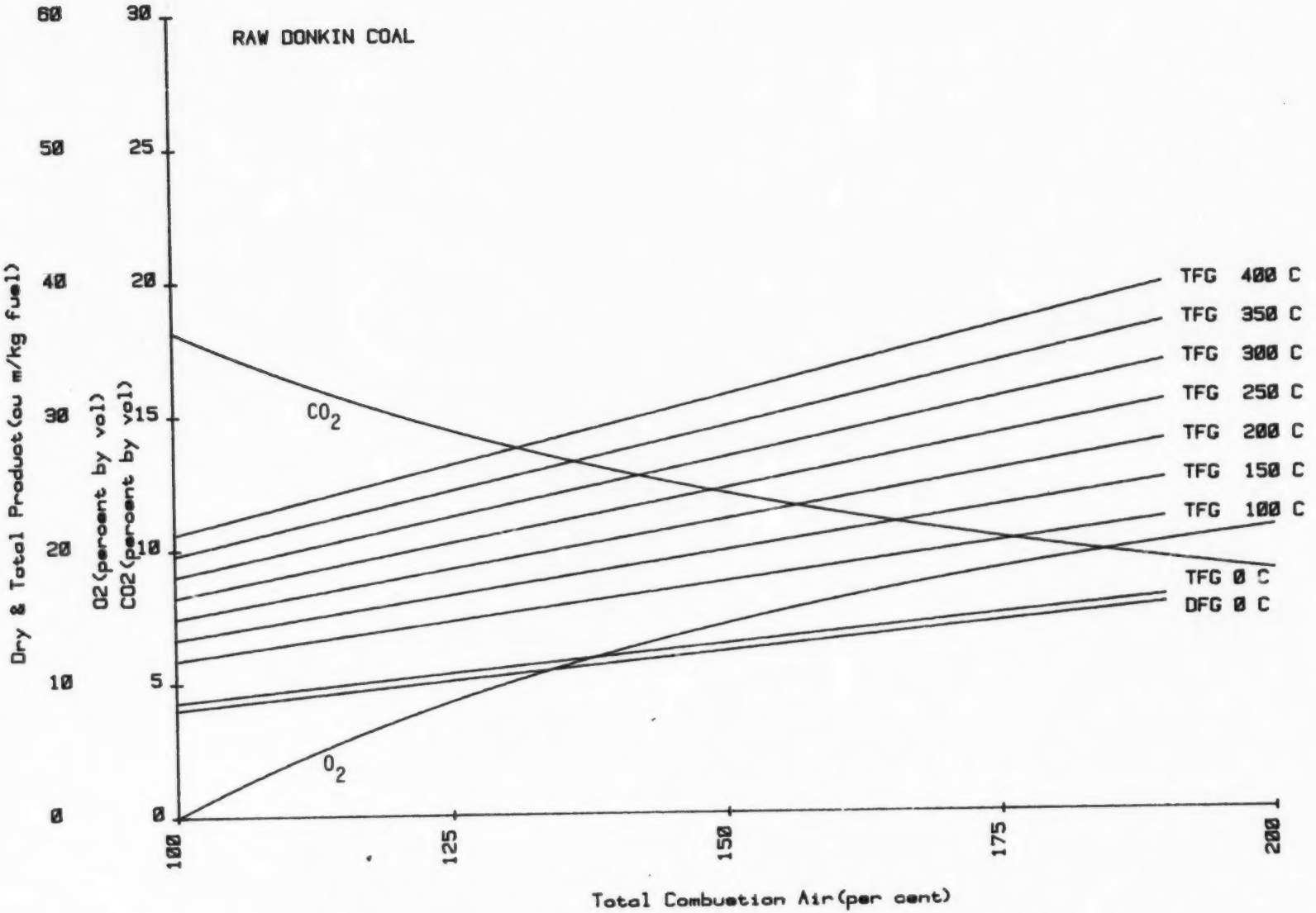


Fig. 2A - Combustion data, volume basis

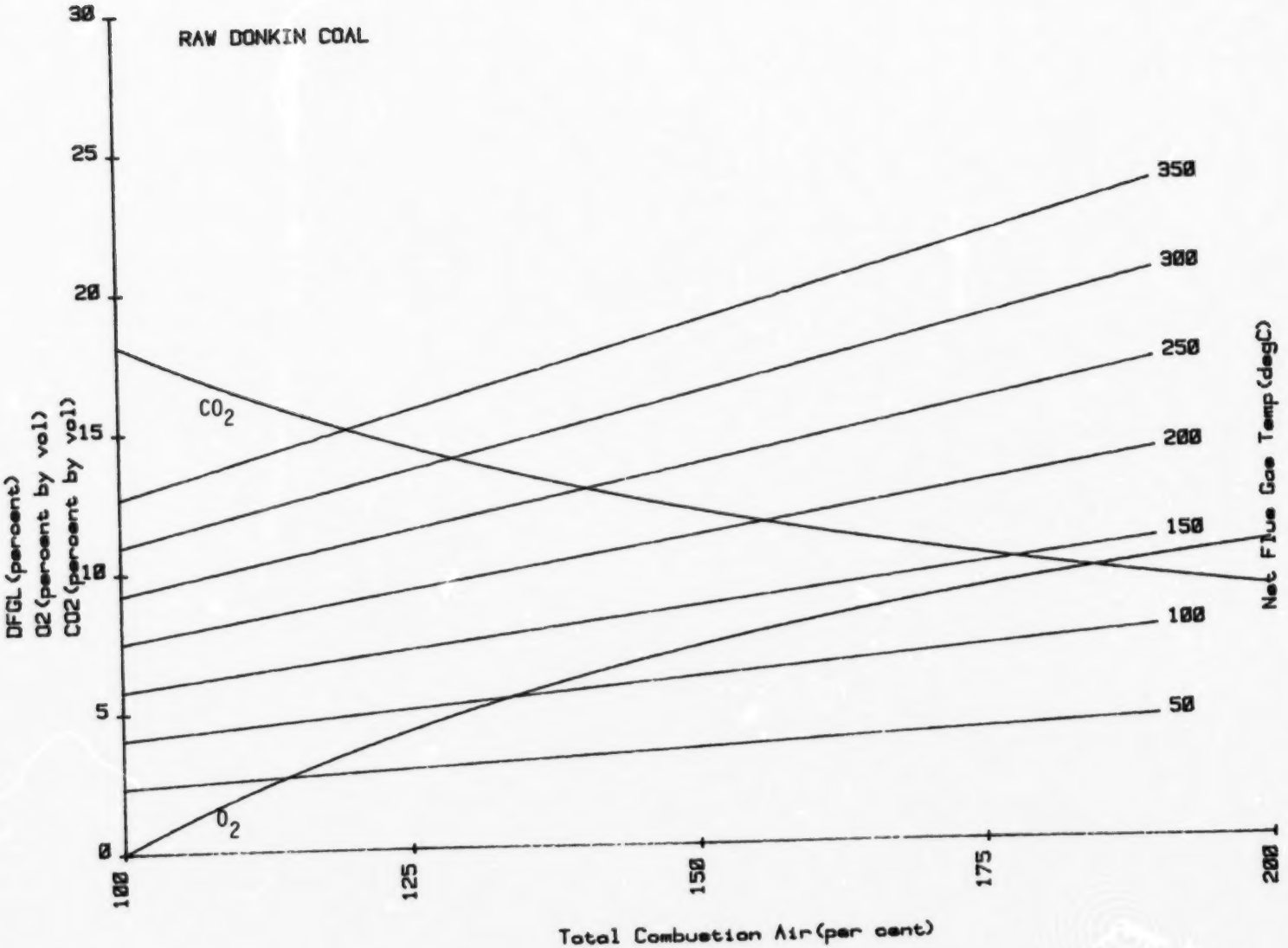


Fig. 3A - Dry flue gas loss for a range of temperature differentials

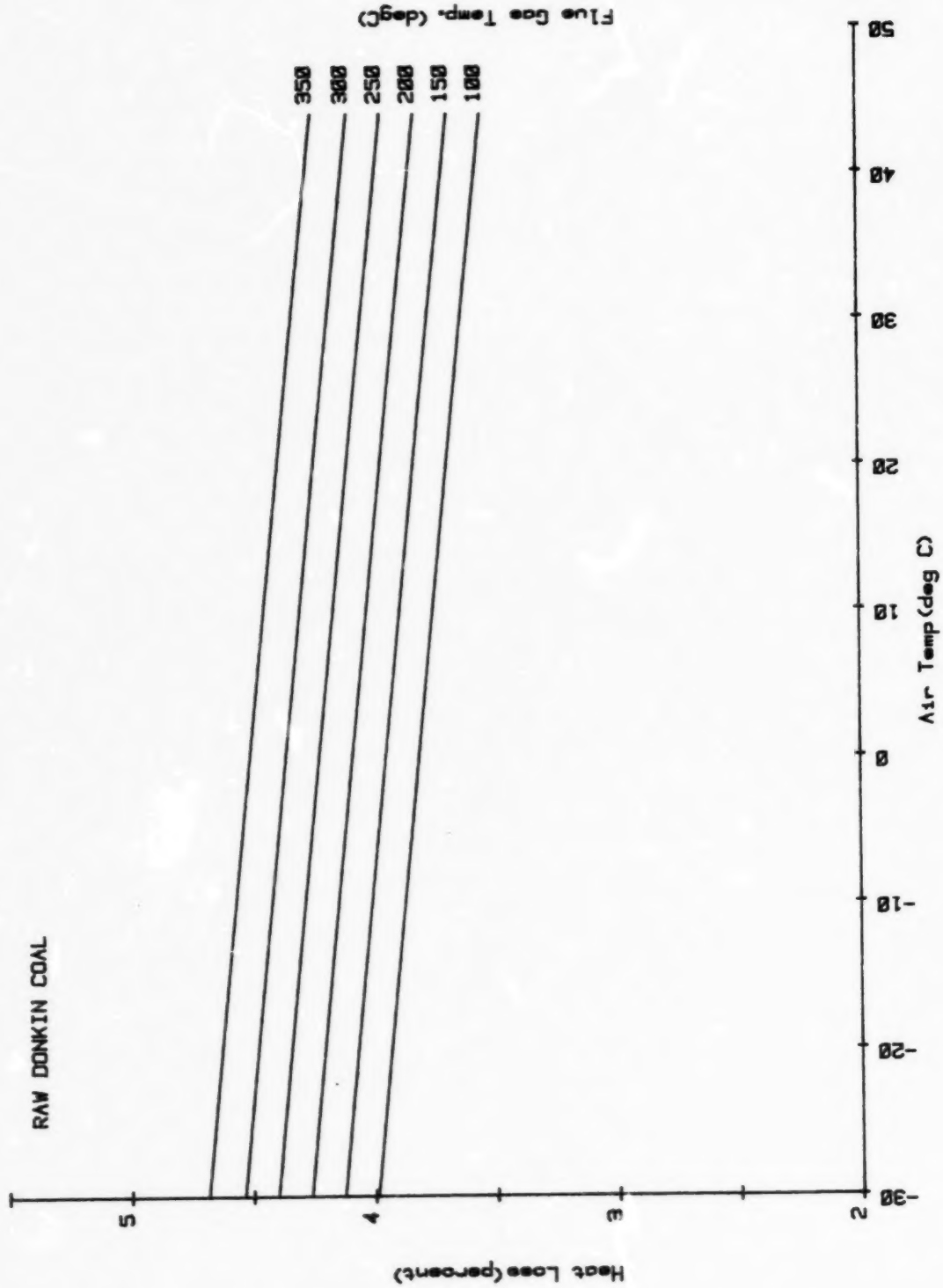


Fig. 4A - Hydrogen loss for a range of stack temperatures

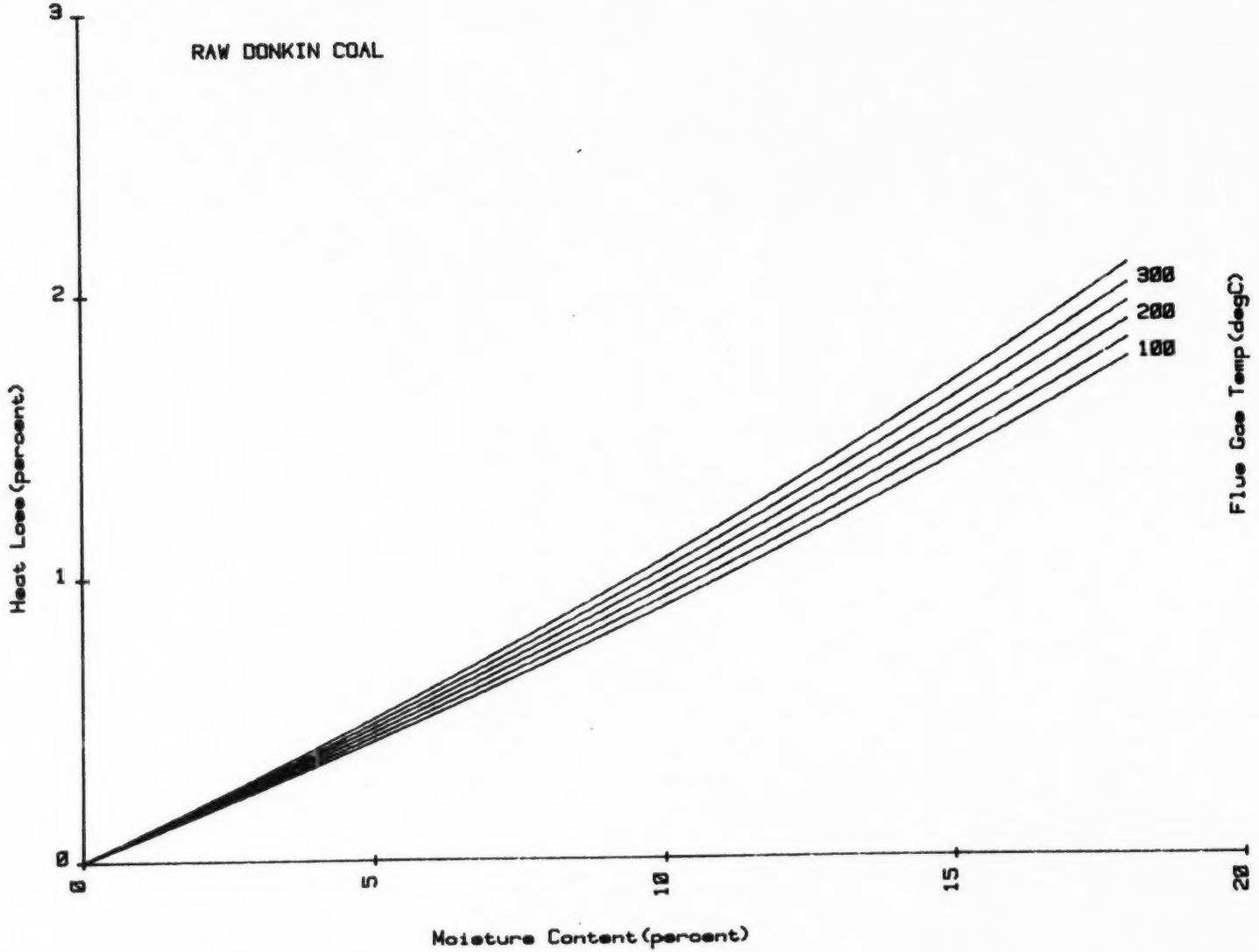


Fig. 5A - Heat loss due to moisture in coal

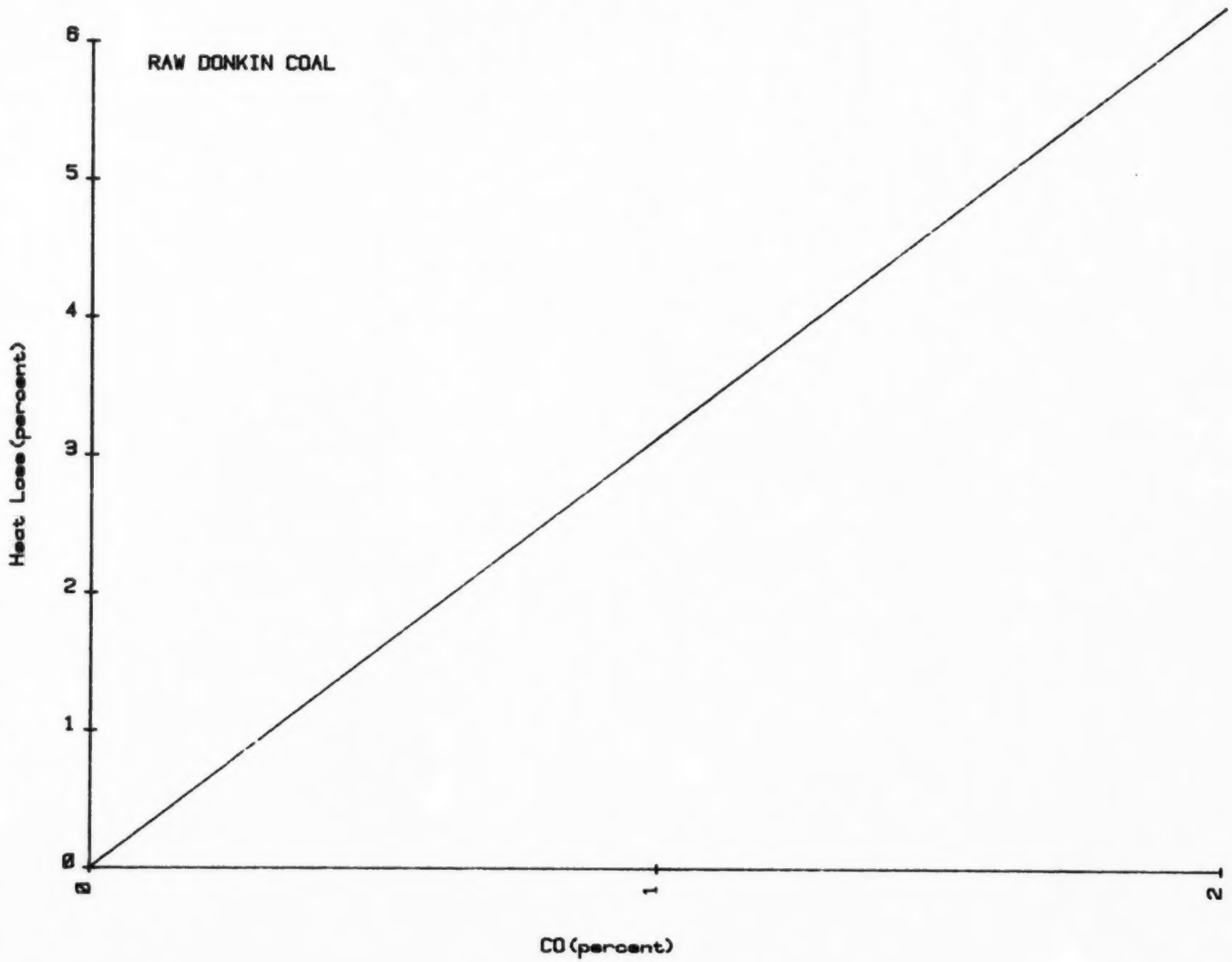


Fig. 6A - Heat loss for a range of CO concentrations, assuming negligible excess air